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Contributed Paper

Fresh Properties of Self-consolidating Concrete Incorporating Palm Oil Fuel Ash as a Supplementary Cementing Material

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ABSTRACT

This paper reports the key fresh properties of self-consolidating concrete (SCC) incorporating palm oil fuel ash (POFA) as a supplementary cementing material. Various SCC mixtures were produced based on the water/binder ratio of 0.50 and 0.60. POFA was incorporated in concretes substituting 0%, 5%, 10%, and 15% of cement by weight. The fresh concretes were tested for the key workability properties of SCC such as filling ability, passing ability, and segregation resistance. The filling ability was determined with respect to slump flow, T_{50cm} spread time, and V-funnel flow time. The passing ability was measured with regard to J-ring flow. The segregation resistance was qualitatively assessed in respect of visual stability index. The segregation resistance was also quantified by sieve and column tests. Test results showed that the slump flow and J-ring flow decreased whereas the T_{50cm} spread time and V-funnel flow time increased with higher POFA content. The presence of POFA improved the stability of concrete mixture and provided a lower visual stability index. In addition, the segregation index and segregation factor obtained from sieve and column tests, respectively, decreased with greater POFA content. The overall findings suggest that the filling ability and passing ability of SCC decreased whereas its segregation resistance increased with higher POFA content.

Keywords: filling ability, palm oil fuel ash, passing ability, segregation resistance, self-consolidating concrete, supplementary cementing material.

1. INTRODUCTION

Self-consolidating concrete (SCC) is a special concrete that spreads under its own weight to reach each and every corner of a formwork without any external means of consolidation [1, 2]. Therefore, SCC is a good choice for many concrete structures where placing and consolidation of normal concrete are difficult due to the complex shape of formwork and congested reinforcement. Mixture proportions and composition of SCC differed from those of ordinary concrete. SCC generally requires a low water/binder (W/B) ratio (0.30–0.40), high cement content, and low amount of coarse aggregate [3]. Besides, SCC needs several ingredients such as supplementary cementing material (SCM) and high-range water reducer (HRWR) in addition to the basic constituents of ordinary concrete. It must need HRWR to achieve the self-consolidation capacity of concrete [4]. SCC can also include SCM mainly to improve the strength and durability of concrete [5]. However, SCM may also influence the key workability properties of SCC such as filling ability, passing ability and segregation resistance [4, 6]. Depending on the type of SCM, this effect can be positive or negative for the aforementioned SCC properties. An SCM increasing the filling ability and passing ability may not be simultaneously efficient in improving the segregation resistance of SCC [3].

The literature search revealed that several SCMs, such as silica fume, ground granulated blast-furnace slag, fly ash and rice husk ash were used to produce SCC with good workability properties, strength and durability [3, 5, 7, 8]. Similarly, palm oil fuel ash (POFA) can be used in SCC. POFA is an agro-waste generated in palm oil industry. It is obtained from the combustion of palm fruit residues of oil palm tree. The oil palm was first introduced in Malaysia in 1870 as an ornamental plant [9]. It is now a leading agricultural cash crop in Malaysia. Currently, there are more than 3 million hectares of palm oil plantation in this country [10]. The palm oil is extracted by pressing the palm fruit bunches of oil palm tree. There are the residues left after the oil extraction at the palm oil mills. The empty fruit bunches (EFBs) are burnt in the boilers to generate steam and electricity for the palm oil mills. EFBs are a suitable raw material for producing steam and electricity for the palm oil mills because a large quantity of these residues is readily available within the plant area. Generally, about 5% POFA by weight of solid wastes is produced after combustion of EFBs [11]. In practice, the POFA produced in the palm oil mills is dumped into the open fields without any profitable return. It causes a nuisance to the environment owing to the disposal in open areas. Since the production of palm oil is increasing continuously in Malaysia, more POFA will be produced and the failure to find any solution for utilizing this ash shall create a severe environmental problem due to uncontrolled disposal. To resolve the environmental problem caused by POFA, several research studies were carried out to examine the feasibility of using this ash as an SCM [11–14]. The research findings showed that POFA can be utilized as a suitable SCM for concrete. It has been used successfully to produce normal, high-strength, and high-performance concretes [11, 13, 15]. In comparison, limited studies have been conducted to produce SCC incorporating POFA as an SCM.

The present study produced different SCC mixtures incorporating POFA in the range of 0–15% of cement by weight. The effects of POFA on the filling ability, passing ability and segregation resistance of SCC were examined in this study. It was found that POFA can be used to produce SCC possessing the aforementioned fresh properties within the acceptable ranges.

2. Materials and Methods

2.1 Constituent Materials

Normal (ASTM Type I) portland cement (C), crushed granite stone, mining sand, ground POFA, normal tap water (W), and HRWR were used in the present study.

The key physical properties of the constituent materials are shown in Table 1. Crushed granite stone was used as the coarse aggregate (CA) and mining sand was used as the fine aggregate (FA) for the concrete mixtures. Both CA and FA fulfilled the BS requirements for aggregate gradation, as can be seen from Figure 1. Cement and POFA together acted as the binder (B) of concretes. POFA was collected from a palm oil mill located in Sungai Buloh, Selangor. The raw POFA collected from the mill was sieved through 400-μm sieve to remove unwanted materials. Then the raw POFA was ground in Los Angeles abrasion machine to obtain the required level of fineness. According to ASTM C 618 [16] and CSA A3001 [17], the mass of fly ash and natural pozzolan passing 45-μm wet sieve shall be at least 66%. This criterion can also be used for POFA. However, the mass of cement passing 45-μm sieve was 84% in the present study. To use POFA as a suitable SCM, it was ground to achieve a percent mass passing 45-μm wet sieve greater than 84%. Forty mild steel rods of 10 mm diameter and 400 mm length were placed into the rotating drum to grind approximately 4 kg of raw POFA. The grinding of POFA was carried out for 16 hours to obtain the desired level of fineness (> 84%). The fineness of POFA was checked at 4 hours grinding interval using a 45-μm sieve in accordance with the procedure given in ASTM C 430 [18]. The sieve fineness of POFA for different grinding periods is shown in Figure 2. After the completion of grinding process, the particle characteristics of POFA were examined by a scanning electron microscope. The particles of ground POFA were porous, angular and irregular, as can be seen from Figure 3.

Ground POFA as well as cement was tested for the chemical composition. X-ray fluorescence (XRF) analysis was carried out to determine the chemical compositions of cement and POFA, as shown in Table 2. This table shows that the deleterious chemical components of cement such as MgO and SO_3 were below the maximum allowable limit specified in ASTM C 150 [19]. In addition, the cumulative mass content of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3) and iron oxide

Table 1. Physical properties of constituent materials.

Material	Properties
Crushed granite stone	Nominal maximum size: 19 mm Specific gravity (saturated surface-dry based): 2.53 Water absorption: 0.6% Fineness modulus: 7.02
Mining sand	Nominal maximum size: 4.75 mm Specific gravity (saturated surface-dry based): 2.62 Water absorption : 1.11% Fineness modulus: 3.11
Ordinary portland cement	Specific gravity: 3.12 % passing 45-μm sieve: 84 Specific surface (m^2/kg): 364.1 (Blaine), 3181 (BET) Pore volume: 0.06 cm^3/g
Ground palm oil fuel ash	Specific gravity: 2.78 % passing 45-μm sieve: 88.4 Specific surface (m^2/kg): 668.9 (Blaine), 4998 (BET) Pore volume: 0.11 cm^3/g
High-range water reducer	Specific gravity: 1.06 Solid content: 13.5%

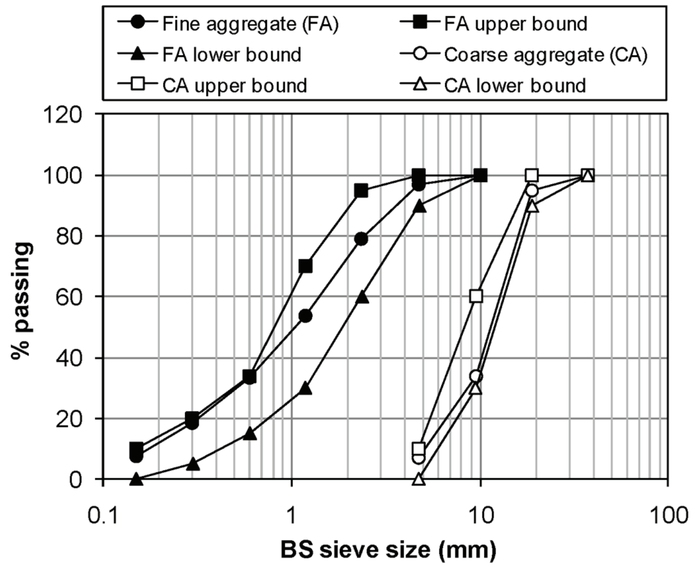

Figure 1. Gradation of aggregates.

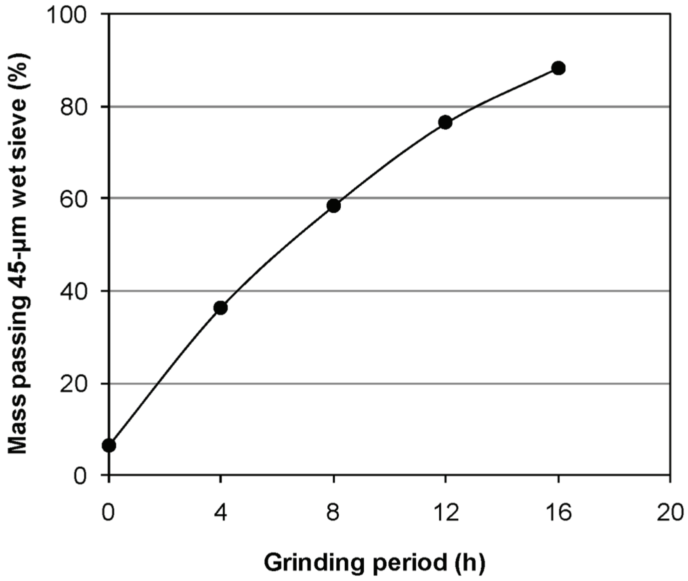

Figure 2. Fineness of POFA with different grinding periods.

(Fe_2O_3) was 89.6% for the POFA used in the present study. Hence, the POFA was a highly pozzolanic supplementary cementing material in accordance with ASTM C 618 [16].

2.2 Mixture Proportions

The mixture proportions of the concretes were determined based on the guidelines given in EFNARC and DOE mix design

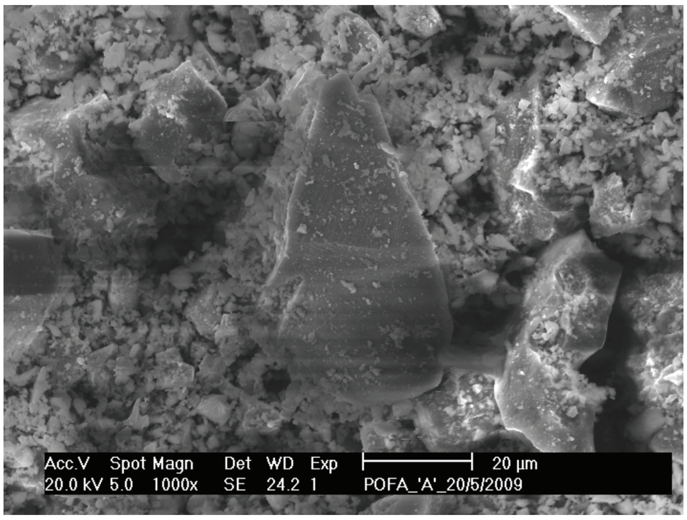

Figure 3. Scanning electron micrograph (SEM) of ground POFA.

Table 2. Chemical compositions of cement and POFA.

Element	Mass content (%)	
	Cement	POFA
Magnesium oxide (MgO)	2.402	1.211
Aluminum oxide (Al_2O_3)	3.443	3.153
Silicon dioxide (SiO_2)	15.713	79.306
Phosphorus pentoxide (P_2O_5)	0.388	2.322
Sulfur trioxide (SO_3)	3.773	0.451
Potassium oxide (K_2O)	0.265	3.233
Calcium oxide (CaO)	70.428	2.793
Titanium dioxide (TiO_2)	0.110	0.235
Manganese oxide (MnO)	0.086	0.072
Iron oxide (Fe_2O_3)	3.343	7.122
Copper oxide (CuO)	0.011	0.016
Zinc oxide (ZnO)	0.001	0.028
Rubidium oxide (Rb_2O)	0.004	0.012
Zirconium dioxide (ZrO_2)	0.008	0.044
Strontium oxide (SrO)	0.025	---

methods [2, 20]. In the present study, eight SCC mixtures (including two control concretes) were produced with relatively high W/B ratios. The W/B ratios of the concretes were 0.50 and 0.60. POFA was used in the concretes substituting 0–15% of cement by weight. The mixture proportions of the concretes are shown in Table 3.

Table 3. Mixture proportions of various SCCs.

Mix. no.	W/B	W kg/m³	C kg/m³	POFA		FA kg/m³	CA kg/m³	HRWR l/m³
				% B	kg/m³			
1	0.50	213.5	410.0	0	-	871.0	876.0	5.03
2	0.50	213.2	389.5	5	20.5	831.0	837.0	5.03
3	0.50	213.4	369.0	10	41.0	830.0	836.0	5.03
4	0.50	213.6	348.5	15	61.5	829.0	835.0	5.03
5	0.60	214.2	342.0	0	-	904.0	910.0	4.84
6	0.60	213.7	324.9	5	17.1	859.0	865.0	4.84
7	0.60	214.0	307.8	10	34.2	859.0	864.0	4.84
8	0.60	214.2	290.7	15	51.3	858.0	863.0	4.84

2.3 Testing of Fresh Concretes

Immediately after the completion of mixing, the fresh concretes were sampled and tested for filling ability, passing ability, and segregation resistance. Slump flow, T_{50cm} spread, and V-funnel flow tests were conducted to measure the filling ability of concrete. The slump flow test was carried out in accordance with ASTM C 1611/C 1611M [21]. The T_{50cm} spread and V-funnel flow tests were carried out according to the procedures given in EFNARC guidelines [2]. The J-ring test was conducted in accordance with ASTM C 1621/C 1621M [22] to measure the passing ability of concrete. The visual inspection of the concrete mass after the slump flow test was carried out to qualitatively assess the segregation resistance of concrete. The concrete mixture was rated with respect to visual stability index (VSI) according to the procedure given in the appendix of ASTM C 1611/C 1611M [21]. In addition, the column and Japanese sieve stability tests were carried out to quantify the segregation resistance of concrete. The column test is more efficient than the Japanese sieve test in detecting the possible segregation of concrete in some members such as column and deep beam [3, 23]. Therefore, the column test should be chosen in such cases to overcome the drawbacks of the Japanese sieve stability test. In the present study, the column stability test was executed following the procedure given in ASTM C 1610/C 1610M [24]. From this test, the segregation factor was determined based on the mass difference of coarse aggregates in top and bottom sections of the column apparatus to express the segregation resistance of concrete. The Japanese sieve stability test was performed based on the procedure developed by Nagataki and Fujiwara [25]. From this test, the segregation index was determined as a ratio of the mortar mass passing the sieve to the mortar mass contained in concrete sample to express the segregation resistance of concrete.

3. Test Results and Discussion

The test results for the filling ability (slump flow, T_{50cm} spread time, and V-funnel flow time), passing ability (J-ring flow), and segregation resistance (segregation index and segregation factor) of different SCC mixtures are given in Table 4. The VSI values of different SCC mixtures are shown in Table 5.

3.1 Filling Ability

3.1.1 Slump flow

The slump flow of concrete varied in

the range of 600-655 mm (refer to Table 4), which indicates a good filling ability of SCC. The slump flow of SCC can differ from 550 mm to 850 mm [26]. However, a minimum slump flow of 600 mm is generally recommended for SCC to ensure adequate self-consolidation capacity [8]. In the present study, the slump flow was higher for the lower W/B ratio, as evident from Table 4. This is mainly due to the increased paste volume and slightly greater HRWR dosage at higher binder content. The increased paste volume and greater HRWR dosage enhanced the dispersion of aggregates with reduced collisions. Furthermore, the slump flow decreased linearly with the increased POFA content at both W/B ratios, as can be seen from Figure 4. This is mostly because of a lesser amount of available free water in the presence of POFA. The POFA particles were more porous and possessed a greater specific surface than cement (see Table 1).

Table 4. Fresh properties of various SCCs.

Mix. no.	W/B	POFA (% B)	Filling ability			Passing ability	Segregation resistance	
			Slump flow (mm)	T_{50cm} spread time (s)	V-funnel flow time (s)	J-ring flow (mm)	Segre. index (%)	Segre. factor (%)
1	0.50	0	655	1.10	1.50	650	23.2	25.2
2		5	655	1.13	1.89	645	22.0	23.8
3		10	650	1.43	2.37	630	15.7	15.7
4		15	630	1.81	2.66	610	11.3	10.9
5	0.60	0	650	0.57	1.35	635	21.3	19.1
6		5	640	0.58	1.64	635	20.2	16.1
7		10	610	0.88	1.99	600	14.7	12.7
8		15	600	0.97	2.52	585	10.2	10.8

Table 5. Visual stability index (VSI) values of various SCCs.

Concrete mix.	Visual inspection	VSI value
1, 5	Significant bleeding, a slight paste ring but no mortar halo, no aggregate pile in the center of the slump flow patty	2 = Unstable
2, 6	Slight bleeding, a very slight paste ring but no mortar halo, no aggregate pile in the center of the slump flow patty	1.5 = Unstable
3, 7	Very slight bleeding, no paste ring or mortar halo, no aggregate pile in the center of the slump flow patty	1 = Stable
4, 8	No bleeding, no paste ring or mortar halo, no aggregate pile in the center of the slump flow patty	0 = Highly stable

The porous POFA particles confined a portion of mixing water due to greater specific surface, and thus reduced the quantity of free water in concrete mixture. Therefore, the water needed for the lubrication action of binder paste became lower in POFA concrete. Consequently, the concrete slump flow was reduced. In addition, the angularity and irregularity of POFA particles contributed to decrease the slump flow of concrete.

3.1.2 T_{50cm} spread time

The T_{50cm} spread time varied from 0.57 s to 1.81 s for different SCC mixtures (see Table 4). This range of T_{50cm} spread time (< 2 s) indicates that the plastic viscosity of concretes was comparatively low [26]. The lower values of T_{50cm} spread time were obtained in the present study due to the use

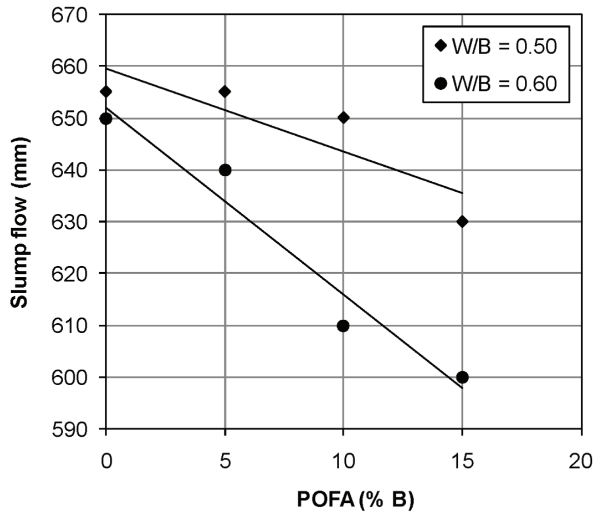

Figure 4. Effect of POFA on slump flow.

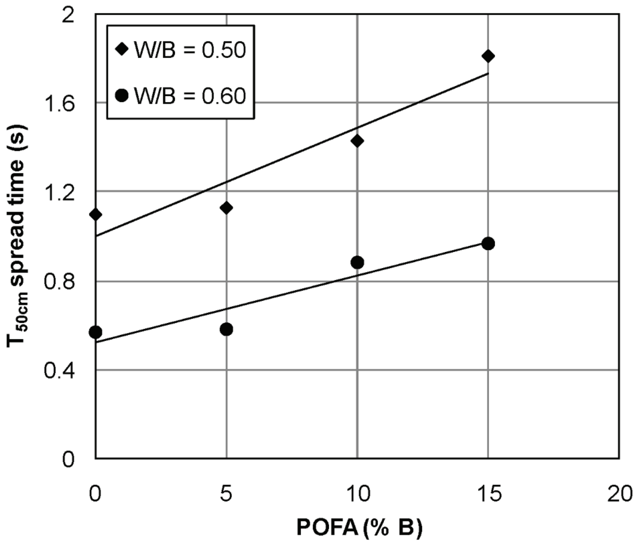

Figure 5. Effect of POFA on T_{50cm} spread time.

of relatively high W/B ratios. However, the T_{50cm} spread times at 0.50 W/B ratio were significantly higher than those at 0.60 W/B ratio, as evident from Table 4. It suggests that the SCC mixtures with 0.50 W/B ratio had a greater plastic viscosity than the SCC mixtures with 0.60 W/B ratio. This is because the free water content was reduced due to the greater binder content at 0.50 W/B ratio. Moreover, for both W/B ratios, the T_{50cm} spread time increased linearly with higher POFA content, as can be seen from Figure 5. The lowest T_{50cm} spread time was obtained for the control concretes (0% POFA). On the contrary, the highest T_{50cm} spread time was achieved for the SCC mixtures with 15% POFA. The increase in T_{50cm} spread time indicates that the plastic viscosity of the concrete increased with higher POFA content. Indeed, the quantity of free water was reduced due to the greater specific surface of POFA. Therefore, the SCC mixture with greater POFA content experienced a higher flow resistance in T_{50cm} spread test. It slowed down the deformation of concrete, and thus a longer time was required for the 50-cm flow spread.

3.1.3 V-funnel flow time

The V-funnel flow time for different SCCs varied in the range of 1.35–2.66 s (refer to Table 4). This range of V-funnel flow time (< 8 s) also indicates that the plastic viscosity of concretes was comparatively low [26]. Alike T_{50cm} spread times, the V-funnel flow times were lower because of relatively high W/B ratios. However, the V-funnel flow times at 0.50 W/B ratio were higher than those at 0.60 W/B ratio, as can be seen from Table 4. In addition, the V-funnel flow time increased linearly with higher POFA content at both W/B ratios, as evident from Figure 6. The lowest V-funnel flow time was obtained for the control concretes (0% POFA). In contrast, the SCC mixtures with 15% POFA provided the highest V-funnel flow time. The higher V-funnel flow times at lower W/B ratio (0.50) and greater POFA content indicated an increase in the plastic viscosity of concrete. This is due to the same reasons as discussed in the case of T_{50cm} spread time.

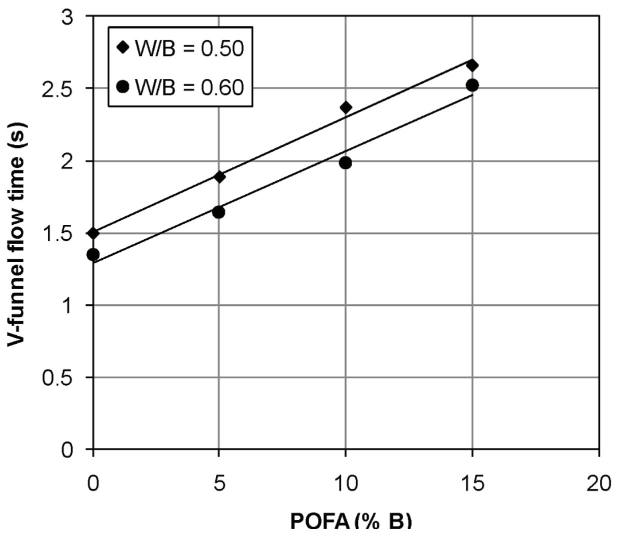

Figure 6. Effect of POFA on V-funnel flow time.

3.2 Passing Ability

3.2.1 J-ring flow

The J-ring flow (slump flow in the presence of a J-ring) varied in the range of 585–650 mm (see Table 4). The difference between slump flow and J-ring flow was 5–20 mm, which indicates excellent passing ability. According to ASTM C 1621/C 1621M [22], no visible blocking occurs when the difference between slump flow and J-ring flow is 0-25 mm. In the present study, the J-ring flow was higher at 0.50 W/B ratio, as compared with 0.60 W/B ratio (refer to Table 4). This is due to the similar reasons that caused to increase the slump flow at lower W/B ratio. Moreover, the J-ring flow decreased linearly with the increased POFA content, as can be seen from Figure 7. The lowest J-ring flow was observed for the SCC mixtures with 15% POFA. In contrast, the highest J-ring flow was attained for the SCC mixtures without any POFA (control concretes). This is owing to the same reasons as discussed in the case of slump flow.

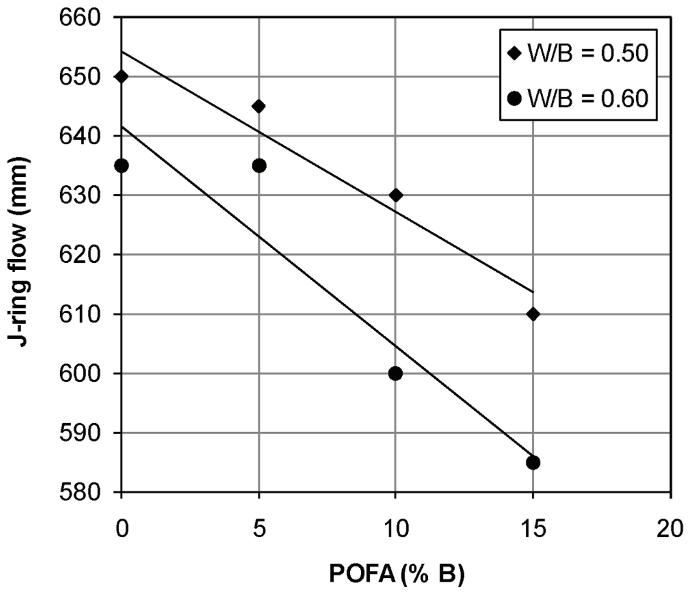

Figure 7. Effect of POFA on J-ring flow.

3.3 Segregation Resistance

3.3.1 Visual stability index (VSI)

The VSI values of the concretes were the same for both W/B ratios (see Table 5). Hence, the effect of W/B ratio on the segregation resistance of concrete was not obvious in visual observation. However, the effect of POFA was evident during visual inspection (refer to Table 5). The concrete mixture with 15% POFA was highly stable with a VSI value of '0' for no evidence of segregation or bleeding. Besides, the concrete with 10% POFA was stable having a VSI value of '1' for no evidence of segregation but a very slight bleeding. The VSI values of these two concretes suggest that they had a good segregation resistance, which was validated by the sieve and column tests (see Table 4). In contrast, the concrete mixture with 5% POFA showed slight bleeding and a very slight paste ring. This concrete was rated as 'unstable' with a VSI value of '1.5'. The worst visual rating was for the concrete with 0% POFA. This concrete was also rated as 'unstable' with a VSI value of '2'. The unstable nature of the concretes with 0% and 5% POFA suggested that they had a poor segregation resistance, which was confirmed by the sieve and column tests (refer to Table 4).

3.3.2 Segregation index

The segregation index of different SCC mixtures obtained from the Japanese sieve stability test varied in the range of 10.2–23.2% depending on the POFA content and W/B ratio (refer to Table 4). A lower value of segregation index indicates a higher segregation resistance. The maximum acceptable limit for the segregation index obtained from the Japanese sieve test is 18% [27]. Hence, the SCC mixtures with 0% and 5% POFA at both W/B ratios failed to have adequate segregation resistance. It is also obvious from Table 4 that the segregation index at 0.50 W/B ratio was slightly higher than that at 0.60 W/B ratio. This is because the concrete spread over the sieve was greater at lower W/B ratio, as understood from the increased slump flow. Consequently, more mortar passed through the openings of sieve after separation from coarse aggregates. A higher amount of mortar passed increases the segregation index, since it is measured as the ratio of mortar mass passing the sieve to the mortar content of concrete.

The segregation index of concrete decreased with higher POFA content at both W/B ratios, as evident from Figure 8. The highest segregation index was obtained with 0% POFA. In contrast, the lowest segregation index was achieved for 15% POFA. The decrease in segregation index at higher POFA content was also related to the reduced spread of concrete.

The effects of W/B ratio and POFA content on segregation index were greatly influenced by the yield strength and plastic viscosity of concrete. The segregation resistance is improved at higher yield strength and greater plastic viscosity of concrete [28, 29]. In the present study, the yield strength and plastic viscosity of concrete were not measured directly. However, the yield strength is strongly correlated with the slump flow – the higher the slump flow,

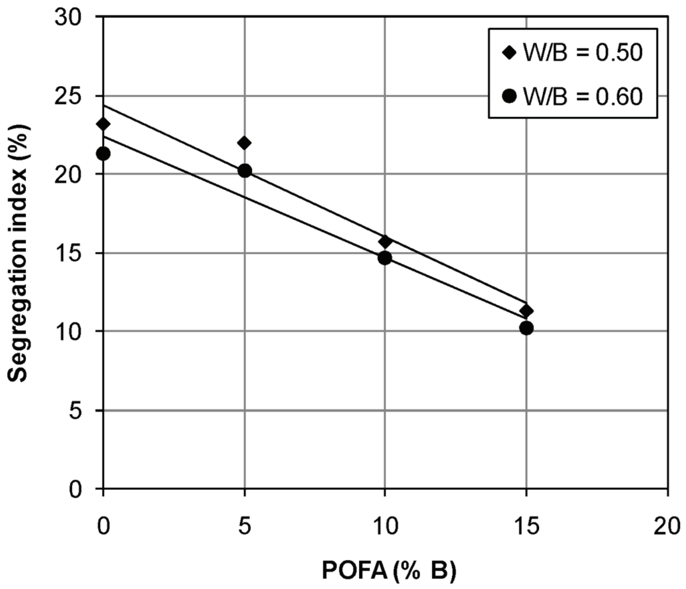

Figure 8. Effect of POFA on segregation index.

the lower is the yield strength [4, 30]. The reduction in slump flow at higher W/B ratio and greater POFA content suggests an increased yield strength, which improves the segregation resistance of concrete and thus gives a lower segregation index. Furthermore, the flow time and plastic viscosity of concrete are well-correlated – the greater the flow time, the higher is the plastic viscosity [4]. Hence, the flow time results obtained from T_{50cm} spread and V-funnel flow tests indicate that the plastic viscosity of concrete increased with higher POFA content. The increased plastic viscosity worked oppositely to decrease the flow spread on the sieve, and thus reduced the segregation index of POFA concrete.

3.3.3 Segregation factor

The segregation factor of different SCCs obtained from the column test ranged from 10.8% to 25.2% (see Table 4). A lower value of segregation factor suggests a higher segregation resistance. The maximum acceptable limit for the segregation factor obtained from the ASTM column test is 15% [31]. Therefore, the SCC mixtures with 0% and 5% POFA at both W/B ratios did not possess adequate segregation resistance. It is also evident from Table 4 that the segregation factor was lower at 0.60 W/B ratio. This is mostly attributed to the increased yield strength of concrete, as understood based on the slump flow results. The higher yield strength decreases the settlement height of aggregates in concrete [29, 31]. Although the plastic viscosity of concrete was lower at 0.60 W/B ratio, as comprehended based on the T_{50cm} spread time and V-funnel flow time results, it was not predominant in increasing the settlement of coarse aggregates. Therefore, the SCC mixtures with higher W/B ratio provided a lower segregation factor.

The segregation factor decreased with greater POFA content, as evident from Figure 9. For both W/B ratios, the highest segregation factor was obtained at 0% POFA, whereas the lowest segregation factor was achieved at 15% POFA. These test results indicate that the settlement of aggregates

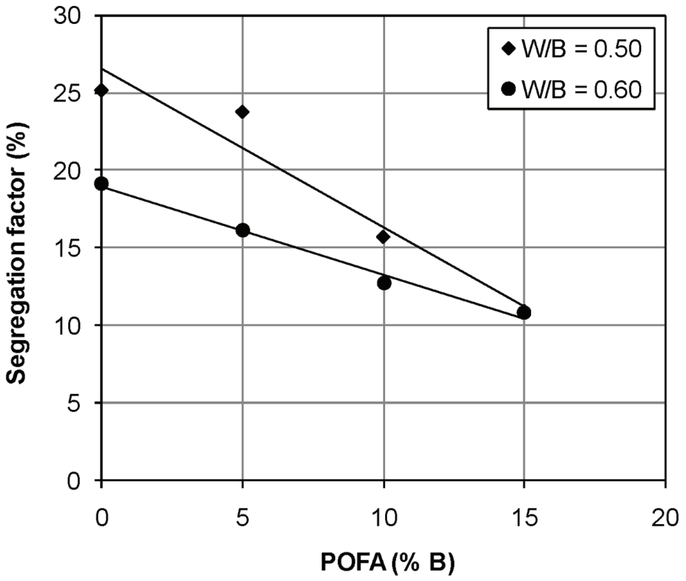

Figure 9. Effect of POFA on segregation factor.

was decreased with greater POFA content. This is attributed to the increased yield stress and plastic viscosity of concrete. The slump flow results indicate that the yield stress of concrete increased with higher POFA content. The increased yield stress decreases the settlement height of coarse aggregates, as discussed earlier regarding the effect of W/B ratio. Moreover, the T_{50cm} spread time and V-funnel flow time results suggest that the plastic viscosity of concrete increased with greater POFA content. The increased plastic viscosity decreases the settlement rate of coarse aggregate, and thus enhances the segregation resistance of concrete [29, 32]. Therefore, the lower segregation factor was obtained at higher POFA content.

4. CONCLUSIONS

The overall outcomes of the present study reveal that the SCC with reasonably good filling ability and passing ability can be produced at relatively high W/B ratios with and without SCM. However, the SCC mixture at high W/B ratios is susceptible to segregation, which can be improved by using an adequate amount of POFA as an SCM.

The specific findings achieved from the experimental investigation on the fresh properties of SCC with and without POFA are summarized below.

a. The slump flow and J-ring flow were higher at the lower W/B ratio. This is because the paste volume increased at a lower W/B ratio due to higher binder content; the increased paste volume enhanced the dispersion of aggregates, and thus produced a greater concrete spread in slump flow and J-ring flow tests.

b. The T_{50cm} spread time and V-funnel flow time increased at the lower W/B ratio. This is because the lower W/B ratio was associated with a higher binder content, which reduces the amount of free water in concrete and thus causes a greater resistance to flow.

c. The slump flow and J-ring flow of concrete decreased, whereas T_{50cm} spread time and V-funnel flow time increased with a greater amount of POFA. This is due to a lesser quantity of available free water in the presence of POFA, which confines some mixing water because of high specific surface.

d. The VSI values were the same for both W/B ratios. However, they became different in the presence of POFA. A higher POFA content improved the stability of concrete mixture and provided a lower VSI value, thus indicating a greater segregation resistance.

e. The segregation index and segregation factor were lower at higher W/B ratio. This is mainly credited to the increased yield strength of concrete, as understood based on the slump flow results.

f. The segregation resistance of concrete improved in the presence of POFA. Hence, both segregation index and segregation factor decreased with higher POFA content. This is due to the increased yield strength and plastic viscosity of concrete, as indicated by the slump flow and T_{50cm} spread time or V-funnel flow time results, respectively.

g. It is possible to produce SCC with adequate filling ability, passing ability and segregation resistance by incorporating POFA as an SCM. At least 10–15% POFA shall be used to improve the segregation resistance of SCC.

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